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X-ray Detection of PSR B1757–24 and its Nebular Tail

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Abstract. We report the first X-ray detection of the radio pulsar PSR B1757–24 using the *Chandra X-ray Observatory*. The image reveals point-source emission at the pulsar position, consistent with being magnetospheric emission from the pulsar. In addition, we detect a faint tail extending nearly $20''$ east of the pulsar, in the same direction and with comparable morphology to the pulsar’s well-studied radio tail. The X-ray tail is unlikely to be emission left behind following the passage of the pulsar, but rather is probably from synchrotron-emitting pulsar wind particles having flow velocity $\sim 7000 \text{ km s}^{-1}$. Assuming the point-source X-ray emission is magnetospheric, the observed X-ray tail represents only $\sim 0.01\%$ of the pulsar’s spin-down luminosity, significantly lower than the analogous efficiencies of most known X-ray nebulae surrounding rotation-powered pulsars.

1. Introduction

PSR B1757–24 is a 124-ms radio pulsar near the supernova remnant (SNR) G5.4–1.2. Radio timing observations show that the pulsar has characteristic age 16 kyr and spin-down luminosity $\dot{E} = 2.6 \times 10^{36} \text{ erg s}^{-1}$ (Manchester et al. 1991). The pulsar is at the tip of a flat-spectrum radio protuberance just

outside the west side of the SNR shell. The protuberance consists of a small, roughly spherical nebula, G5.27–0.90, that has a highly collimated finger of emission on its western side. The pulsar is at the westernmost tip of the finger, whose morphology and spectrum suggest a ram-pressure confined pulsar wind nebula (PWN) (Frail & Kulkarni 1991). Assuming the pulsar was born at the center of G5.4–1.2 and that the characteristic pulsar age is a good estimate for the age of a system, the pulsar appears to have overtaken the expanding shell, implying a transverse space velocity of $v_t \sim 1800 \text{ km s}^{-1}$ for a distance of 5 kpc (Frail, Kassim, & Weiler 1994). However, recent interferometric observations failed to detect the implied proper motion (Gaensler & Frail 2000). They set a 5σ upper limit of $v_t < 590 \text{ km s}^{-1}$. This suggests that the pulsar is older than its characteristic age, or that the assumed pulsar birth place is incorrect.

A ram-pressure confined wind should radiate X-rays as part of the broadband synchrotron spectrum that results from the shock-acceleration and subsequent gyration of relativistic wind electron/positron pairs in the ambient magnetic field. This is in contrast to static PWNe in which a high external pressure, usually supplied by the hot gas interior of a SNR, does the confining. The PSR B1757–24 PWN is of interest as it exhibits the cleanest and most extreme bow-shock plus tail morphology of any such system, suggesting that it may exemplify the class of ram-pressure confined PWN most ideally. We summarize here the first X-ray detection of PSR B1757–24. Details of this result can be found in Kaspi et al. (2001).

2. Observations

The PSR B1757–24 field was observed on 2000 April 12 for 19.6 ks using the S3 back-illuminated chip on the Advanced CCD Imaging Spectrometer (ACIS) instrument aboard the *Chandra X-ray Observatory*. The ACIS image (Fig. 1, left) reveals a faint point source near the radio pulsar position, and a fainter tail of emission on the eastern side, similar to the radio emission. Figure 1 (right) shows the distribution of counts as a function of distance from the point source. With respect to the mean and the western side, the eastern side clearly has an overdensity of counts extending nearly $20''$ from the point source. Careful astrometry confirms the coincidence between the X-ray point source and the radio pulsar.

The spectrum of the point source is well characterized with both an absorbed power-law model, as well as an absorbed thermal bremsstrahlung model. The spectrum of the fainter tail emission is not well determined, however it is suggested of relatively hard emission, having power-law index of ~ 1 .

3. Results and Discussion

The X-ray point source is likely to be non-thermal pulse-phase-averaged magnetospheric emission from the radio pulsar itself. The observed 2–10 keV unabsorbed luminosity, for a distance $d = 5 \text{ kpc}$ is $2 \times 10^{33} \text{ erg s}^{-1}$, assuming beaming angle $\phi = \pi \text{ sr}$ (see Kaspi et al. 2001). This implies an efficiency of conversion of spin-down luminosity into magnetospheric emission of $0.00020(\phi/\pi \text{ sr})(d/5 \text{ kpc})^2$. This efficiency, as well as the measured power-law

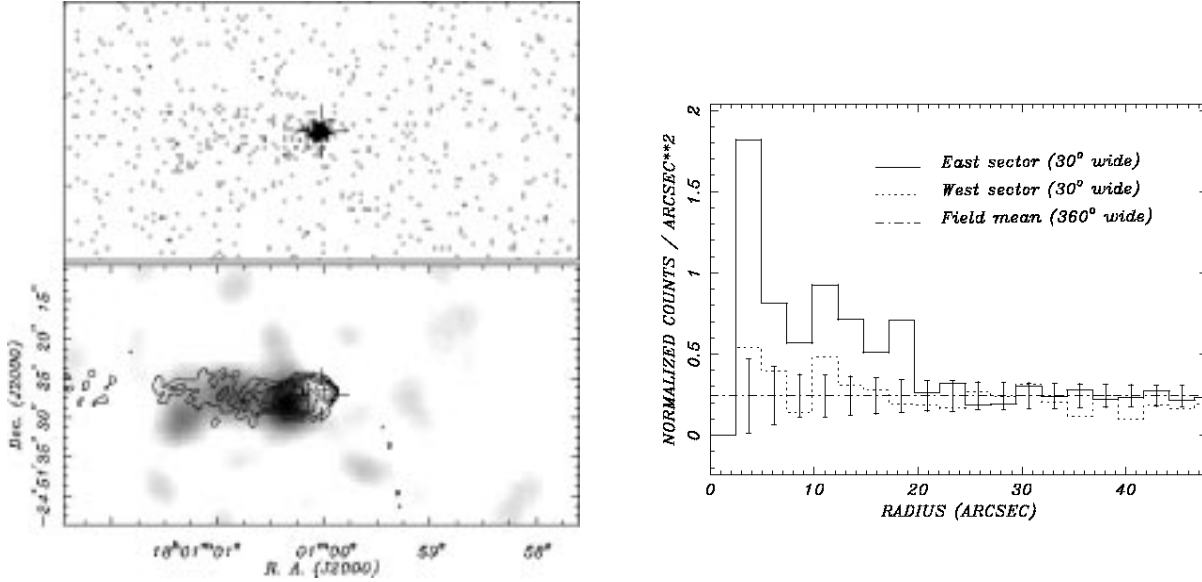


Figure 1. Left: (Top) Image in 0.3 – 10 keV range. The X-ray point source is at the pulsar position (the cross). (Bottom) Same image with point source contribution removed, $\sim 2''$ Gaussian smoothing, and intensity scaled to emphasize diffuse X-ray emission. Contours show 4.9 GHz radio emission in equally spaced contours ranging from 0.17 to 0.56 mJy/beam (beam size $1''.2$). Right: X-ray intensity vs. radius from the point source in two 30° wedges, east (solid line) and west (dotted line) of the pulsar. The point-source emission has been subtracted. The field mean is shown by a dot-dashed line.

photon index, are consistent with those observed for the magnetospheric components of other radio pulsars (Becker & Trümper 1997).

The tail X-ray emission is likely to be synchrotron radiation from the shocked pulsar wind. The observed X-ray tail extends nearly $20''$, or 0.48 pc for a distance of 5 kpc, to the east of the pulsar, nearly as long as the detected radio tail. The upper limit on the transverse velocity of $v_t < 590 \text{ km s}^{-1}$ implies the time since the pulsar was at the eastern-most tip of the observed X-ray emission must be $> 800 \text{ yr}$. The synchrotron lifetime of a photon of energy E (in keV) in a magnetic field B_{-4} (in units of 10^{-4} G) is $t_s \simeq 40E^{-1/2}B_{-4}^{-3/2} \text{ yr}$. Thus, for $t_s > 800 \text{ yr}$ and $E \simeq 1 - 9 \text{ keV}$, $B < 0.8 - 14 \mu\text{G}$. This is much less than the equipartition magnetic field $B_{\text{eq}} \sim \sqrt{\dot{E}/r_s^2 c} \sim 70 \mu\text{G}$ expected in the vicinity of the pulsar. Here, r_s is the distance from the pulsar to the bow shock head. Hence, the X-ray tail behind PSR B1757–24 cannot be synchrotron emission from pulsar wind particles just left behind after the passage of the pulsar. Rather, freshly shocked wind particles must be continuously fed eastward with a velocity much larger than the pulsar space velocity, $v_f \gg v_t$. We can constrain the flow velocity v_f of the wind particles in the tail by noting that it must be high enough to continuously supply particles given their cooling times. Thus, the flow time $t_f \lesssim t_s$. Assuming that the

magnetic field reaches its equipartition value near the bow-shock head and that this value holds for the approximately one-dimensional tail region too, we find $t_s \gtrsim 70(E/1 \text{ keV})^{-1/2}(B_{\text{eq}}/70 \text{ } \mu\text{G})^{-3/2} \text{ yr}$. As the tail extends to 0.48 pc for $d = 5 \text{ kpc}$, this implies $v_f \gtrsim 6700(d/5 \text{ kpc})(E/1 \text{ keV})^{1/2}(B_{\text{eq}}/70 \text{ } \mu\text{G})^{3/2} \text{ km s}^{-1}$.

The tail emission has low flux. The tail surface brightness in the 2–8 keV band is $4.5 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$, with uncertainty of $\sim 30\%$. The total unabsorbed flux in the 2–8 keV band in our extraction region is $9.8 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$, with similar uncertainty. The efficiency with which the pulsar's \dot{E} is converted into tail X-rays in the 2–8 keV band is only $0.00011(d/5 \text{ kpc})^2$, roughly half of the point-source efficiency. This is in contrast to other rotation-powered pulsars, like the Crab, whose X-ray nebular emission is much brighter than the point-source output. Without timing information, we cannot rule out an ultra-compact nebula as the source of the point-source emission. Several effects may reduce the X-ray efficiency of ram pressure confined PWNs. First, the efficiency of conversion of \dot{E} into X-ray emitting particles may be lower since the reverse shock in the ram-pressure-confined PWNs is strong only in the forward part of the head, subtending a much smaller solid angle than in a static PWN. Second, a low X-ray efficiency is expected if the flow time of the relativistic plasma through the tail is shorter than the synchrotron life time. A similar argument was put forth (Chevalier 2000) to explain the low efficiencies of the Vela and CTB 80 pulsars. Finally, low surface brightness emission from beyond the eastern tip of the observable X-ray tail, or even from G5.27–0.90, have gone undetected in our observation. Emission from the direction of that nebula, having X-ray surface brightness half of the ACIS-S3 background, would contribute roughly two orders of magnitude more flux.

No emission is detected from the shell supernova remnant G5.4–1.2. The upper limits on remnant emission are unconstraining.

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